Enhanced Visualization of the Knee Joint Functional Articulation Based on Helical Axis Method

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Abstract. Comprehensive descriptions of the motion in articulating joints open new opportunities in biomedical engineering. The helical axis is a established method that describes flexion-extension at joints, which currently lacks an intuitive visualization. In this paper, we present a comprehensive visualization of knee joint motion based on a direct measurement of the helical axis. The proposed approach incorporates the three-dimensional motion of patient-specific bone segments and the representation of helical axes on the bone, facilitating the observation of the flexion-extension motion at the knee joint.

1 Introduction

Within the medical field, the axis of rotation about the knee joint is commonly discussed in order to improve joint functionality and increase prosthesis longevity. The generally adopted method to define this axis depends on anatomical landmarks and is widely considered as a fixed axis throughout motion [1]. However, this practice has proven to have inter- and intra- individual discrepancies [2].

The description of motion based on helical axes has been verified to be superior within the biomechanical engineering field, removing repeatability errors [3, 4]. In contrast to the fixed axis of rotation, the description of a bone motion in three-dimensional space can be more faithfully captured in terms of a temporal sequence of helical axes $HA[t]$ and angles of flexion $\alpha[t]$ with respect to a reference bone (Fig. 1) [5].

Comprehensive 3D representations are needed to further understand methods describing motions, e.g. [1]. However, the existing applications used to calculate helical axes lack an intuitive visualization to analyse states and conditions. Besier et al [3] represent their helical data with 2D graphical plots, i.e. alongside the conventionally captured gait curve. Bogert et al [4] represent helical axes by lines passing through a 2D illustration of a joint model and use a numbering system to depict the temporal evolution of the axes. Until now studies have been realized under these premises. In particular, such approaches lack an interactive

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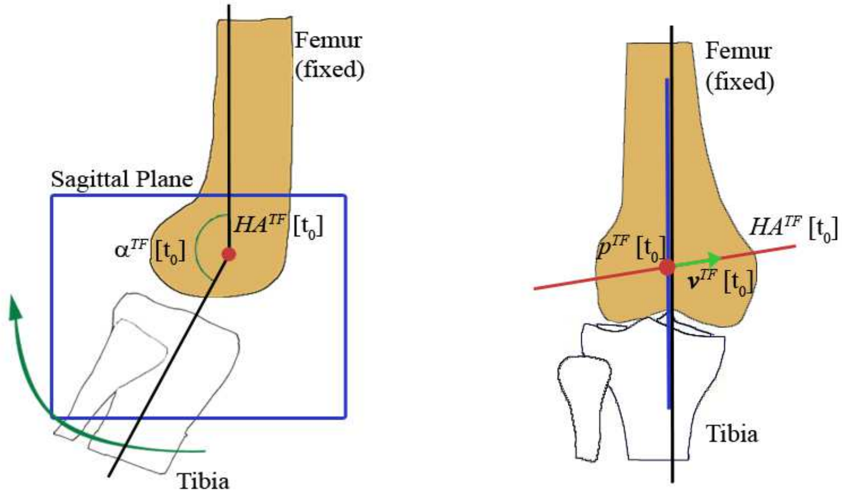
3D visualization to represent the temporal evolution of the helical axes $HA[t]$ together with patient-specific bone segments, which facilitates the understanding of the motion.

In this paper, we present a visualization that enriches the joint motion representation based on a direct measurement of helical axes. We focus on the representation of the knee joint flexion-extension motion. The implemented approach visualizes the three-dimensional motion of patient specific bone segments and the representation of helical axes on the bone, facilitating the description of the knee flexion-extension motion for kinematical studies and surgery applications.

2 Material and methods

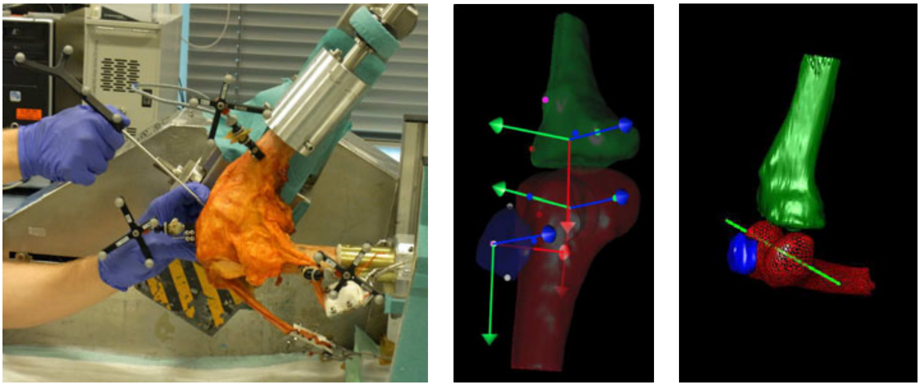
We have applied our proposed approach in the context of the experimental work described in [6]. Extending upon this work, in the following subsection we describe the data collection process employed in order to calculate helical axes data from biomechanical experiments applied to specific specimens. Afterwards, in Sec. 2.2 we describe how that data is merged with information obtained in CT scans of the respective specimen in order to visualize the knee joint flexion and helical axes.



(a) Sagittal view (b) Frontal view

Fig. 1. Helical axes of tibia with respect to the femur (reference bone) $HA^{TF}[t]$, composed of instantaneous centers of rotation and direction vectors $HA^{TF}[t] = (p^{TF}[t], \boldsymbol{v}^{TF}[t])$, defined in three-dimensional space. The angle $\alpha^{TF}[t]$ is defined between the axes attached to the femur and to the tibia, both of them being contained in the sagittal plane. $HA^{TF}[t]$ and $\alpha^{TF}[t]$ characterize the flexion-extension motion of the tibia with respect to the femur along the time t.

Fig. 2. Helical data collection setup with the tracking coordinate system T_E (a). Landmarks on the bone's surfaces L_V defined in the viewer to obtain the coordinate system T_V (b). 3D Representation of the knee joint flexion and helical axis $HA_V^{TF}[t]$ (c).



(a) Experimental setup [6] (b) Defining T_V (c) Knee joint motion

2.1 Helical axes data collection

The data collection was performed with the help of a specifically designed in vitro knee simulator (Fig. 2a). Freshly frozen cadaver knee joints were prepared by removing skin and subcutaneous tissue, whilst keeping the articular capsule intact. The femur was fixed in position and the tibia was fixed to a lever arm that constrains the tibia to flexion-extension but further the tibia has complete freedom of motion. The simulator applied loads to the quadriceps and hamstring tendons, forcing the knee specimen to complete an extension motion.

The tracking of bone motion was performed using a two camera Polaris Optical Tracking System[1], with passive reflective marker tools rigidly fixed to the femur, tibia and patella providing rigid bone motion at an accuracy of 0.35mm at 10Hz. The tracking yields the temporal evolution of the helical axis $HA_E^{TF}[t]$ and angle $\alpha_E^{TF}[t]$ (tibia to femur) as well as $HA_E^{PF}[t]$ and $\alpha_E^{PF}[t]$ (patella to femur) with respect to a fixed tracking coordinate system T_E used in the experiment. We calculate this data by using an adaptation of the algorithm presented in [5] that extracts the centres of rotation $p[t]$ and direction vectors $v[t]$ from the tracked marker positions with accuracy improvements proposed in [7]. This refined adaptation was implemented within the LabVIEW platform[2]. Additionally, a set of standardized characteristic anatomical landmarks L_E found on the bone's surfaces [8] was also acquired (referenced with respect to T_E), which is used in the mapping of coordinate systems of the experiment within the viewer. This acquisition is made manually by touching specific points of the bones with a passive reflective marker pointer device.

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[1] Polaris Optical Tracking System, Northern Digital Inc., USA

[2] LabVIEW [online] http://www.ni.com/labview/

2.2 Data processing for visualization

Our viewer of the joint motion was implemented in Java using the Java3D API[3]. It constitutes a module for the open platform for 3D visualization and 3D segmentation of medical data YaDiV [9].

Within our viewer, CT images (512 × 512 × 163) of the considered specimen are accurately segmented, thereby obtaining a 3D segment-visualization of the femur, tibia and patella. Then, a set of significant landmarks L_V is identified according to those used in the experimental setup, on the bone segment surfaces within in the viewer (Fig. 2b). These landmarks can be specified using manual or automated approaches, also on MRI images [10]. Afterwards a matching between L_E and L_V is used to establish the mapping between the experimental reference frame T_E and the reference frame T_V used within in the viewer. Finally, the helical axes data collected in Sec. 2.1 is transformed into the viewer reference system, thereby yielding $HA_V^{TF}[t], \alpha_V^{TF}[t]$ and $HA_V^{PF}[t], \alpha_V^{PF}[t]$. This information can now be directly used to provide a 3D representation (Fig. 2c).

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[3] Java3D [online] https://java3d.java.net/

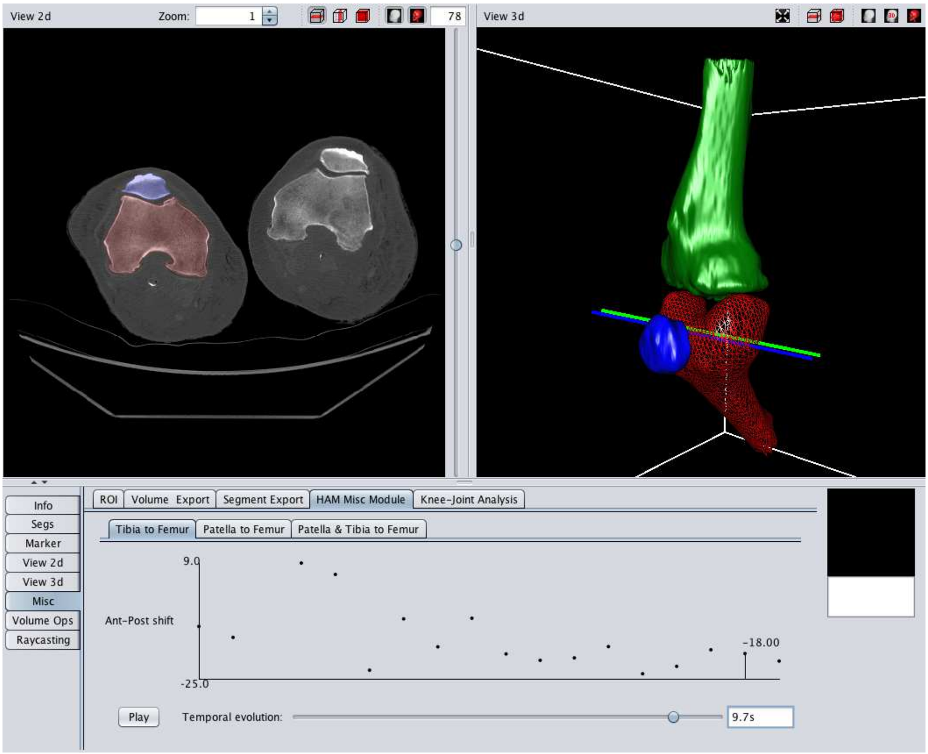

Fig. 3. Visualization of a healthy knee joint completing flexion-extension motion from experimental data, including the helical axes $HA_V^{TF}[t]$ (green) and $HA_V^{PF}[t]$ (blue).

3 Results

The implemented visualization (Fig. 3) has the following functionalities:

- The 3D view (Fig. 3, top right) shows the spatial configuration of helical axes $HA_V^{TF}[t], HA_V^{PF}[t]$, including the centers of rotation $p_V^{TF}[t], p_V^{PF}[t]$ for a fixed time t. By varying t, the view reproduces the patient-specific motion of the knee, according to $\alpha_V^{TF}[t]$ and $\alpha_V^{PF}[t]$.
- The 2D sub-panel views (Fig. 3, bottom) present analytical data concerning the translations of the centers of rotation $p_V^{TF}[t], p_V^{PF}[t]$ (i.e. indicating anterior and posterior shifts). Both 2D and 3D views are synchronized in time, supporting a rapid interpretation of the motion.

4 Discussion

Compared to the previous approaches referenced in Sec. 1, the realistic visualization of bone motion incorporating helical axis data provides a more understandable and precise representation of the knee joint functional articulation. This visualization can facilitate biomechanical engineers to localize the functional flexion axis in terms of anatomical bone motion.

The introduction of the helical axes viewer can be highly beneficial for surgical intervention, as surgeons often try to replicate the joints original and healthy functionality during total knee replacement. Moreover, we expect our approach to be commonly applicable, since optical tracking systems similar to the one utilized here (Sec. 2.1) are already used during total knee replacement surgeries. In our ongoing research, we plan to conduct further data acquisition of knee joint motion related to several surgery techniques and to provide an extended analysis and visualization of helical axis data. This will facilitate the interpretation of diverse states throughout deterioration and the pre-post intervention comparison.

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